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ROLE OF PHOSPHORUS IN EUTROPHICATION

A. F. Bartsch

National Environmental Research Center
Corvallis, Oregon

August 1972

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SECTION I

CONCLUSIONS

In light of our present knowledge of eutrophication, its causes and prospects for control, following are appropriate conclusions:

1. It is affirmed that limiting phosphorus availability in lakes is the single, most important and necessary step to be taken now in eutrophication control.

2. The most effective way to do this is to reduce phosphorus inputs.

3. Because all inputs are additive, and therefore potentially significant, all should be considered for control.

4. Municipal sewage is the major point source. All such discharges to lakes and other susceptible waters should be treated to reduce phosphorus content to realistic target levels.

5. Phosphorus contributions to sewage should be reduced in every feasible way.

6. Nutrient budgets should be established for all major lakes to facilitate curtailing nutrient inputs from all significant diffuse and point sources.

7. Technology, where not at hand, must be developed to effectively curtail phosphorus inputs from all significant point and diffuse sources.

8. Where slow flushing impedes improvement from curtailed phosphorus inputs, accessory steps to inactivate, harvest, or otherwise retrieve nutrients from lakes must be considered.

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16. Abstract

The process of eutrophication is a natural one, often accelerated greatly by man's activities that contribute nutrients. The key nutrient is phosphorus. Although there is no simple relationship, it is clear that increasing phosphorus content frequently leads to accelerated eutrophication. Of all important nutrients, phosphorus is most controllable.

Sources of phosphorus include runoff from undisturbed agricultural and urban lands; waste from watercraft; industrial and domestic wastes; biological sources; and precipitation. Also, the most important single source is municipal sewage, fortunately, the most potentially controllable of all inputs.

Control efforts follow five basic directions: Limiting fertility; improving food webs; stimulating plant diseases and parasites; recycling nutrient-laden water to agricultural and forest lands; and using toxic chemicals to kill vegetation. Limitation of nutrients is the most desirable approach, particularly through curtailing phosphorus inputs.

17a. Descriptors

*Eutrophication, nutrients, algal blooms, primary productivity, trophic levels

17b. Identifiers

*Phosphorus, detergents

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SECTION II

INTRODUCTION

During the past several decades a growing anxiety has appeared among environmentalists, government officials, and the general public over the obvious and continuing deterioration of the Nation's lakes. In many of them, changes in water quality and usefulness have been perceptible in a single human lifetime, and in some lakes, such as Lake Erie, change has been even more rapid. These changes are eutrophication, which has many symptoms. Excess growths of algae and other aquatic plants are the most destructive and distasteful ones.

Many interacting factors contribute to the overall process of eutrophication--a term known more widely now to mean the nutrient enrichment of waters. Once in motion, eutrophication brings on a number of related changes in addition to increased production of algae and other aquatic plants--deterioration of desirable fisheries and water quality, and other responses that impair water uses and are found objectionable.

In whatever way lakes originated, they soon acquired nutrients from the earth, the air, and the remains of plants and animals. If sufficient in amount, these nutrients supported growing aquatic plants. As inputs continued, fertility and productivity increased, in many cases reaching considerable levels. Changes like these still go on but at differing paces in different lakes, the rate varying at different times, sometimes the direction of change even reversing. Natural factors that functioned during past centuries or millenia have left some lakes relatively untouched as pristine lakes--Lake Tahoe in California, Crater and Waldo lakes in Oregon, for example. Others, exposed during a similar time span, have reached advanced stages of natural eutrophication. In their new eutrophic character, such lakes now range from ones with the blemish of frequent dense algal blooms* to a plot of dry land that shows where the now extinct lake once had been.

It has been known for at least 50 years that people accelerate eutrophication. Such resulting change can be rapid and occur in years to tens of years where human populations are sufficiently dense. Rarely is the human influence as bizarre or direct as in the Lake of Blood (Lago Yarquacocha) high in the Andes (1). Here, according to legend, the continual bloom of blue-green algae depends on a persistent rich supply of nitrogen and phosphorus from the time, during the Inca wars, when 10,000 dead warriors were thrown into the lake.

Thus, one can distinguish "natural" from "accelerated," "artificial," or "cultural" eutrophication. But such changes can be largely reversed

*Dense populations of free-floating algae that give the water a greenish, often peasoup, appearance.

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if the human influence is eliminated in time. At least some lakes are changing faster under the influence of people than the rate of human population growth. Unless resolute steps are taken, further impacts on lakes and increasing threats of destruction must be expected. Very likely, also, these influences will intensify as population grows beyond the present 205,000,000 persons. The human influence of greatest concern is our persistent habit of augmenting lake fertility far beyond the pace of natural contributions. It is readily apparent that this human threat is real and cause for national concern.

Eutrophication is a worldwide problem. Because the human influence has prevailed longer in some other countries, they also have a longer recorded history of cultural eutrophication than the United States. But here, too, the problem is growing more prominent and widespread than a few decades ago. Through the press, many persons now are aware of trouble in the Great Lakes, the St. Lawrence River, the Potomac Estuary, and many other threatened waters. While it is not known how many of this Nation's 100,000 small lakes are afflicted, a recent preliminary survey (2) shows the problem occurring with some intensity in at least 40 of the 50 states. In states well endowed with lakes which contribute substantially to the economy, the dollar losses from impaired recreation, depressed resort patronage, property depreciation, and costs of ameliorating the problem certainly must extend to hundreds of millions of dollars annually. In these states, and especially in others not so well endowed with water where the competition for it is more keen, the loss of lakes for citizen use is perhaps even more serious.

Full-blown eutrophication is obvious to most people, but when it is only beginning, the scientist must search out the more subtle symptoms for signals of impending trouble. They include (3, 4, 5, 6, 7, 8): (a) analytical detection of increased amounts of nutrients, (b) measurable increases in algal populations, (c) decreasing transparency of the water, (d) in deep lakes that stratify thermally, gradually decreasing dissolved oxygen in the bottom water, (e) decreasing organism diversity, sometimes preceded briefly by increasing diversity, (f) appearance of new, undesirable species and disappearance of old ones, and (g) increased silting and accelerated accumulation of bottom sediments which add to the other signs that eutrophication progress should be a matter of public concern.

Publications related to this subject number in the thousands. It is not possible, therefore, to cite here more than a handful that bear in some important way on the significance of phosphorus in eutrophication. The serious student is referred to the Eutrophication Information Center at the University of Wisconsin as a national repository for much of the world's pertinent literature. For the interested reader, the following would give general or comprehensive coverage of eutrophication:

Eutrophication: Causes, Consequences, Correctives (9)

Science Year, 1971 (10)

Algae and Metropolitan Wastes (11)

Environmental Requirements of Blue-Green Algae (12)

Eutrophication - A Review (13)

Modeling of the Eutrophication Process (14)

Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters, with Particular Reference to Nitrogen and Phosphorus as Factors in Eutrophication (6)

Eutrophication (15)

I wish here to say "thank you" for the helpful assistance of Dr. G. A. Rohlich, formerly Director,* and staff of the Water Resources Center, Unversity of Wisconsin, at Madison, and Dr. J. R. Vallentyne, Scientific Leader, Eutrophication Section, Freshwater Institute, Winnipeg, Canada. The following colleagues in the National Environmental Research Center, Corvallis, were most helpful, also, in providing pertinent data, ideas, and continuing counsel in connection with this document: Mr. Daniel F. Krawczyk, Chief, Consolidated Laboratory Services; Mr. Thomas E. Maloney, Chief, Dr. Kenneth W. Malueg, Chief, Lake Restoration Section, and Dr. Charles F. Powers, Chief, Technology Development Section, of the National Eutrophication Research Program; and Dr. L. P. Seyb, Assistant Director, Pacific Northwest Water Laboratory.

*Presently, he is C. W. Cook Professor of Environmental Engineering, University of Texas, Austin.

SECTION III

CAUSES OF EUTROPHICATION

This section explores the questions of how and why lakes and other waters become eutrophic. It is generally believed that lakes originally are oligotrophic--low in nutrients, relatively deep, with low productivity and ample oxygen in the deep water (hypolimnion). As time passes, the lake is enriched, productivity increases, hypolimnetic dissolved oxygen is reduced by decay and mineralization processes, and the lake basin begins to fill. It is becoming a eutrophic lake. Ultimately, eutrophication leads to the lake's extinction. Lakes in the midpoint of these changes are mesotrophic. Graphic representation of this concept is shown in Fig. 1 (15).

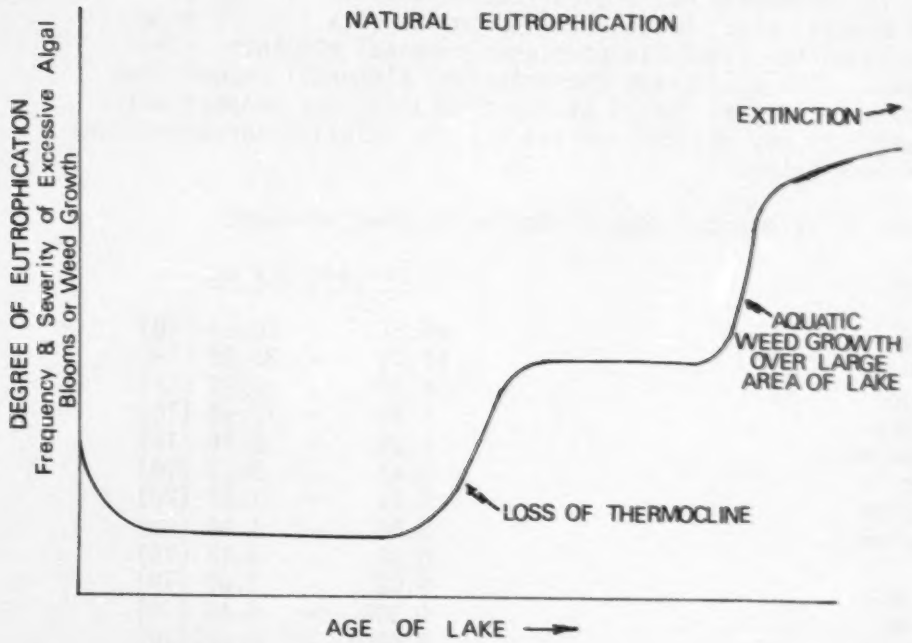
NATURAL EUTROPHICATION
DEGREE OF EUTROPHICATION
Frequency & Severity of Excessive Algal Blooms or Weed Growth
EXTINCTION
AQUATIC WEED GROWTH OVER LARGE AREA OF LAKE
LOSS OF THERMOCLINE
AGE OF LAKE

Fig. 1 Progressive Changes in Natural Eutrophication
From Lee (15)

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Ample scientific evidence supports this concept. The earliest known documentation of eutrophication symptoms dates to Biblical days and mention of the red coloring of the Nile (Exodus 7:20-21), no doubt caused by algae. Evidence has been found (16) of man-induced eutrophication as early as 191 B. C. in Lake Monterosi during the building of the Via Cassia by the Romans. Paleolimnological investigations of lake sediments (17) also retrace the process of eutrophication through the years. Man's influence seems to be expanding ever since these early times in the expression of accelerated eutrophication.

The most significant single factor in stimulating eutrophication is nutrient input from the lake's drainage basin. If basin land is fertile, the lake water very probably will be fertile. If the basin is large in relation to lake volume, opportunities for nutrient input from cities, farms, and other sources are multiplied. Lakes that have a small or infertile drainage basin, such as Crater Lake with only 163 square miles, receive little input in contrast with others, such as Upper Klamath Lake, Oregon, with 3,810 square miles, of which some are cultivated.

Thus, fertility obviously has a quantitative aspect. It has a qualitative aspect, also, because the potential of a lake to grow plants depends on the right mix of needed chemical elements. The following table (Table 1) gives the principal elemental composition of some freshwater algae. While at least implying the proportionate nutrient needs, it may not reflect exactly the relative concentrations required in lake water.

Table 1. Elemental Composition of Freshwater Algae

Element	Percent dry wt.
Carbon	49.51 - 70.17 (18)
Oxygen	17.40 - 33.20 (18)
Hydrogen	6.57 - 10.20 (18)
Nitrogen	1.39 - 10.98 (18)
Phosphorus	1.35 - 2.76 (19)
Sulfur	0.42 - 0.77 (19)
Magnesium	0.26 - 1.51 (20)
Potassium	0.04 - 1.44 (20)
Iron	0.02 - 3.45 (19)
Manganese	0.02 - 2.60 (19)
Calcium	0.006 - 0.40 (19)
Strontium	0.0004 - 0.051(19)
Copper	0.0008 - 0.034(19)
Zinc	0.0004 - 0.009(19)
Silicon	1.00 - 50.00 (21)

In addition to these elements, extremely minute amounts of others, such as molybdenum, cobalt, sodium, boron, and vanadium are required in the nutrition of some algae. Vitamin B_{12}, thiamine, and biotin are important, also.

A lake's algal production rate is governed by the simultaneous operation of a number of controlling factors. Nutrient availability is but a single, though exceedingly important requirement. The historical performances of numerous lakes verify that the extent of production generally is related directly to nutrient abundance (5, 22). This relationship can be demonstrated easily with laboratory algal assays, giving knowledge to affirm that nutrient-rich lakes are expected to produce large algal crops. It also helps explain why the total of human activities that increase nutrient levels in various ways so strikingly accelerate eutrophication. The following table (Table 2) expresses this principle by showing approximate photosynthetic rates of free-floating algae (phytoplankton) that occur in response to increasing nutrient supplies that become available as lakes shift from oligotrophy to eutrophy.

Table 2.* Photosynthetic Rates of Phytoplankton in Oligotrophic and Eutrophic Lakes

	Oligotrophic**	Eutrophic	
		Natural**	Polluted**
Mean rates in growing season	30 - 100	300 - 1,000	1,500 - 3,000 mg C/m^2/day***
Annual rates	7 - 25	75 - 250	350 - 700 g C/m^2/year***

* Modified from Vollenweider (6).

** Oligotrophic = poor in nutrients; natural = rich in nutrients; polluted = very rich in nutrients.

*** If these values of carbon fixed per square meter per day or year (representing photosynthetic rate) are multiplied by 2, they approximate the algal weight.

Another expression of a lake's response to increasing fertility is the maximum plankton density or standing crop attained during the year: ultra-oligotrophic lakes, less than 1 cm^3/m^3; highly eutrophic lakes, more or less exceeding a value of 10 cm^3/m^3; and mesotrophic lakes, between these two limits (6).

Major controlling factors in addition to nutrient supplies include lake morphology, geography, climate, and temperature. Mean depth is the most significant dimension (23), and large, deep lakes are more resistant to eutrophying influences than small, shallow ones.

Availability of light energy to trigger photosynthesis is another principal factor influencing biological production. Effectiveness of incoming light depends on: (a) the extent to which algal cells are kept suspended in the surface-lighted layer by turbulence, and (b) the depth of the layer in which light is sufficient for effective photosynthesis. If the volume of the lake participating in photosynthesis is large in relation to total volume, as in shallow lakes, the lake will tend toward eutrophic characteristics.

In addition, the greater the length of the shoreline, generally the greater the productivity. This is because of greater contact of water with land, more bays and coves, more shallow water area for weed growth, greater diversification of bottom and margin conditions, less exposed shoal water, and greater extension of photosynthesis to the bottom. This latter point is particularly important because the closer and more permanent the association of the photosynthetic and decomposition zones, the greater the productivity.

Summer temperature distribution in a lake is determined largely by configuration of the lake basin and its depth, latitude, and degree of protection from wind. Shallow lakes with gently sloping basins resist stratification throughout the summer, while deep lakes with more precipitous topography tend to stratify into an upper epilimnion, a well-developed thermocline, and a lower hypolimnion. Then the thermocline acts as a barrier to movement of nutrients from the hypolimnion and sediment into the photosynthetic zone. This happens even though considerable sedimented phosphorus may dissolve in the hypolimnion at times when oxygen is depleted.

SECTION IV

SIGNIFICANCE OF PHOSPHORUS

Ample and increasing nutrients have been identified as a major factor in fostering eutrophication. There are five important points related to nutrients: (a) a variety is needed, (b) as nutrients increase, production rate and algal crop size usually increase, (c) accelerated eutrophication and increasing nitrogen and phosphorus concentrations commonly proceed together, (d) oligotrophic lakes usually are phosphorus limited, and (e) as accelerated eutrophication proceeds, the nitrogen/phosphorus ratio commonly diminishes with the result that phosphorus is no longer limiting. The qualitative and quantitative aspects represented by points a and b have already been discussed.

Studies of eutrophication in numerous lakes around the world have contributed to better understanding of how nutrients are involved. In analyzing the roles of nitrogen and phosphorus, recognized as key nutrients in the process, Vollenweider (6) has drawn upon data for numerous lakes, especially those in Europe. In this context, he explored the significance of nitrogen and phosphorus from two points of view: (a) concentrations available for algal use at a given point in the annual cycle and (b) rates of supply. He (6) commented on concentration as follows: "Looking upon the results of these analyses as a whole, it can be said that the critical levels suggested by Sawyer [24] for the permissible nitrogen and phosphorus concentrations [less than 10 µg/l inorganic phosphorus and less than 300 µg/l inorganic nitrogen] are borne out, by and large, by conditions existing in the lakes of Central Europe. Of the two, phosphorus is the more critical...."

As shown in Table 3 below, phosphorus and nitrogen levels found in the Great Lakes substantially agree with these stated critical levels in relation to their trophic states:

Table 3. Nitrogen and Phosphorus Concentrations in the Great Lakes

	Total P, µg/l	Total N, µg/l
Oligotrophic		
Lake Superior	5 (25), 9 (27)	2-71 (27)
Lake Huron	10 (25), 13 (27)	340 (27)
Oligo-mesotrophic		
Lake Michigan	13 (25), 7-21 (28)	60*(27)
Lake Erie	20 (26), 10 (27)	420 (27), 470 (26)
Eutrophic		
Lake Erie	61 (25)	
Western Basin	50 (26), 93 (27)	710 (27), 740 (26)
Central Basin	30 (26), 16 (27)	430 (27), 470 (26)
Lake Ontario	75 (25), 13 (27)	60*(27)

*NH_3-N only

Using nutrient input data for 30 lakes in Europe and North America, Vollenweider (6) also analyzed for trophic state of lakes in relation to nutrient loading rate. It was concluded that rates are more significant than maximum concentrations that may occur. Similar analyses have been made by NERP* for several lakes in the United States. While both the European and American data are somewhat limited, the following points are significant. First, a commonly occurring feature of oligotrophic lakes, such as Lake Tahoe and Waldo Lake, is a total phosphorus loading less than 0.2 $g/m^2/yr$, and total nitrogen loading, probably less than 5 $g/m^2/yr$. Second, fairly serious eutrophication, as in Zürichsee (6), Lake Erie and other lakes, is to be expected with a total phosphorus loading greater than 1 $g/m^2/yr$ and nitrogen loading of 10 $g/m^2/yr$. Third, the specific critical loading level that separates oligotrophic and eutrophic waters is probably around 0.2-0.5 g total $P/m^2/yr$ and 5-10 g total $N/m^2/yr$. Fourth, no simple relationship can be expected among nutrient loading, nutrient concentration, and production because of a variety of other influencing factors such as depth, extent of shoreline, flow-through, and detention time as pointed out on page 9. Nevertheless, the following table (Table 4) provides tentative practical guidelines that are worthy of control consideration.

Table 4.** Permissible Loading Levels for Total Nitrogen and Total Phosphorus

(g/m^2 year)

Mean depth up to:	Permissible loading, up to: N	P	Dangerous loading in excess of: N	P
5 m	1.0	0.07	2.0	0.13
10 m	1.5	0.10	3.0	0.20
50 m	4.0	0.25	8.0	0.50
100 m	6.0	0.40	12.0	0.80
150 m	7.5	0.50	15.0	1.00
200 m	9.0	0.60	18.0	1.20

** Modified from Vollenweider (6)

Not many United States lakes can be checked against this table because nutrient budgets have not been established. But, certainly, for the following examples, loading, lake status, and lake vulnerability are in agreement with it:

* National Eutrophication Research Program, EPA, National Environmental Research Center, Corvallis, Oregon.

Oligotrophic lakes

Waldo Lake, Oregon (29) - mean depth, 35.7 meters
Estimated input: P 0.0026 $g/m^2/yr$
N 0.19 $g/m^2/yr$

Lake Tahoe, Calif.-Nev. (30) - mean depth, 249 meters
Estimated input: P 0.04 $g/m^2/yr$
N 0.23 $g/m^2/yr$

Oligo-mesotrophic lakes

Lake Michigan (31) - mean depth, 76.0 meters
Estimated input: P 0.13 $g/m^2/yr$
N 1.3 $g/m^2/yr$

Eutrophic lakes

Shagawa Lake, Minn. (29) - mean depth, 6.7 meters
Input: P 0.93 $g/m^2/yr$
N 7.3 $g/m^2/yr$

Lake Erie, 1967 (26) - mean depth, 17.7 meters
Input: P 1.6 $g/m^2/yr$
N 6.8 $g/m^2/yr$

Lake Ontario, 1967 (26) - mean depth, 84 meters
Input: P 0.65 $g/m^2/yr$
N 8.3 $g/m^2/yr$

Algae, like many other microorganisms, have a similar elemental composition. While differing somewhat among species, mixed algal populations contain carbon, nitrogen, and phosphorus in a weight ratio approximating 41 carbon, 7.2 nitrogen, and 1 phosphorus.* While perhaps not exact for all algae, this ratio suggests the pattern of nutrient requirements and availability ratios in the environment that one would expect to be near ideal. Further, in keeping with Liebig's Law of the Minimum (32), the essential nutrient present in least supply relative to need will limit growth and thus determine size of the algal crop.** This means that if the environment offers 82 weight units of carbon, 14.4 of nitrogen, but only 1 of phosphorus, growth will be limited by a deficiency of phosphorus because there is only half as much as needed. Adding phosphorus in abundance at this point via sewage or otherwise will destroy its growth-regulating function. This, unfortunately, is what is now taking place at many localities in this country. This

*This equals an atomic ratio of 106 C, 16 N, and 1 P (34).
**In nature the circumstances may be somewhat more complex in detail because alga populations are mixtures of species with differing nutrient requirements and differing demands at different times.

mechanism is an important key in the eutrophication problem and prospects for control.

A related concern is a resulting gradual decrease in the nitrogen/phosphorus ratio in many lakes as they receive sewage or other high phosphorus-bearing pollutants. Oligotrophic lakes commonly have N/P weight ratios of 15 or more and then are usually phosphorus limited, but, with accelerated eutrophication, the ratios decrease progressively. At some points in Western Lake Erie, the weights ratio shifted from 15 to 5 in 14 years as NO_3-N increased 50 percent and PO_4-P percent (33). However, for the lake as a whole, the 1967 ratio was still near 15 (26). In Lake Ontario the 1967 ratio was 30. In eutrophic Upper Klamath Lake the ratio is 5.6 (by weight) whereas in Oregon's ultra-oligotrophic Waldo Lake it is 75. Lake Tahoe is an exception in remaining oligotrophic, with an estimated ratio of 7 or less; it is also nitrogen limited (30).

Such undesirable shifts in nitrogen/phosphorus ratios usually result from sewage pollution and other human activities that increase nitrogen and phosphorus inputs at differing rates. Where sewage pollution is substantial, sewage, with its nitrogen/phosphorus weight ratio of about 2-3 (36), adds phosphorus at a proportionately much greater rate than nitrogen. As a result, the added phosphorus, reaching an excess and no longer limiting, triggers a new productive response. This actively proceeds until exhaustion of nitrogen, some other nutrient, or other environmental shift impedes continued production. In this process, lake status shifts in the direction of eutrophication. The greater the increase in phosphorus, the greater the shift is likely to be. Documented case histories for many lakes, including Lake Washington at Seattle (7, 37), Zürichsee in Switzerland (5, 38), lakes in Germany (39), and Lake Fure in Denmark, bear this out (22). It is therefore characteristic of sewage-polluted eutrophying lakes that phosphorus concentrations increase considerably with continuing phosphorus pollution, Fig. 2.

Similarly important is the fact that in numerous lakes that have been studied, when overall production is low, as in oligotrophic ones, phosphorus concentrations typically are low (less than 5-20 µg/l). In such lakes the usual factor limiting production is lack of phosphorus (6). This fact was also expressed by Thomas (5) on the basis of studies on 40 European lakes: "It is certain, moreover, that oligotrophic lakes on which man has had little or no influence all have phosphate as the limiting factor." Lund (35) also found that the addition of 10 µg PO_4-P/l alone to Lake Buttermere (England) led to a massive development of diatoms and a reduction of soluble silica content in the water -- showing that phosphorus had been limiting.

Vallentyne (40) recently summarized the reported experience in fish pond fertilization. In short, it shows that addition of phosphate alone or inorganic fertilizer containing phosphate stimulates

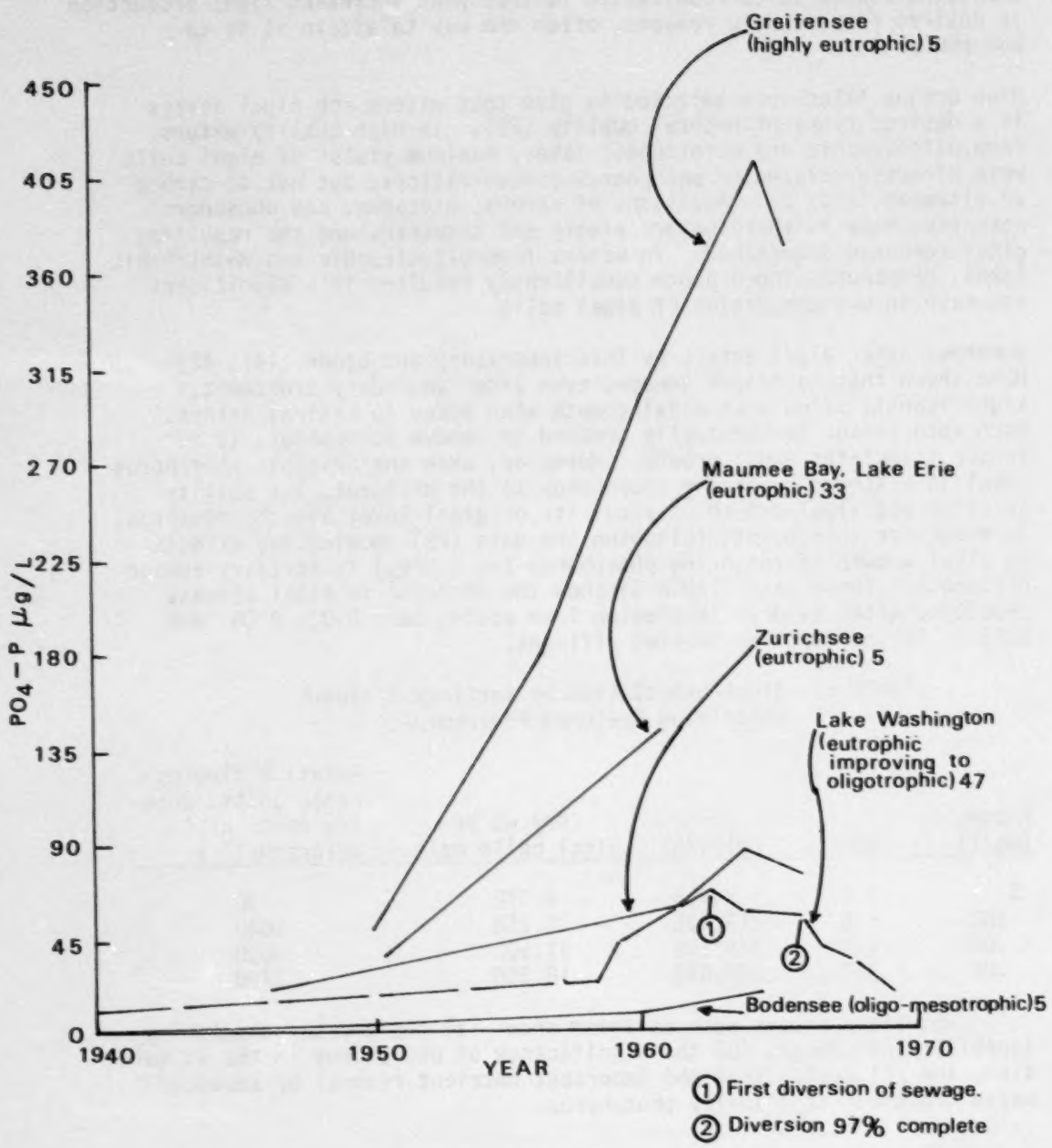

Fig. 2 Increasing Phosphorus Concentrations in Phosphorus-Polluted Lakes

increased production of algae that form the base of fish food supplies. The significance from a practical viewpoint is that fertilizing with phosphate increased yields of fish of from 50 to 500 percent or more. The significance to eutrophication is that when increased algal production is desired for economic reasons, often the way to attain it is to add phosphorus.

Nine Oregon lakes were selected to give test waters for algal assays in a desired range of natural quality (29). In high quality waters from oligotrophic and mesotrophic lakes, maximum yields of algal cells were directly related to phosphorus concentrations, but not to carbon or nitrogen (Fig. 3). Additions of carbon, nitrogen, and phosphorus were also made to these waters singly and together, and the resulting algal response determined. In waters from oligotrophic and mesotrophic lakes, phosphorus added alone consistently resulted in a significant increase in maximum yields of algal cells.

Numerous other algal assays by this laboratory and others (41, 42) have shown that municipal sewage, even after secondary treatment, significantly stimulates algal growth when added to natural waters. When such sewage is chemically treated to remove phosphorus, it no longer stimulates algal growth. Moreover, when the original phosphorus level is restored by adding phosphorus to the effluent, its ability to stimulate algal growth at about its original level also is restored. To emphasize this point, following are data (29) showing the effects on algal growth of restoring phosphorus (as K_2HPO_4) to tertiary sewage effluents. These data (Table 5) show the increase in algal biomass resulting after 14 days incubation from adding back 0.02, 0.04, and 0.06 mg P/l to tertiary treated effluent.

Table 5. Algal Stimulation by Tertiary Effluent Containing Restored Phosphorus

P-conc. (mg/l)	pH	Cells/ml	Dry wt of algal cells mg/l	Relative fluorescence units, showing conc. of chlorophyll a
0	7.6	3,718	0.078	30
.02	7.6	213,136	7.250	5040
.04	7.7	348,196	11.500	5000
.06	7.7	643,645	18.300	5700

Laboratory assays such as these show: (a) the growth-stimulating capability of sewage, (b) the significance of phosphorus in the stimulation, and (c) verify that the important nutrient removal by advanced waste treatment is actually phosphorus.

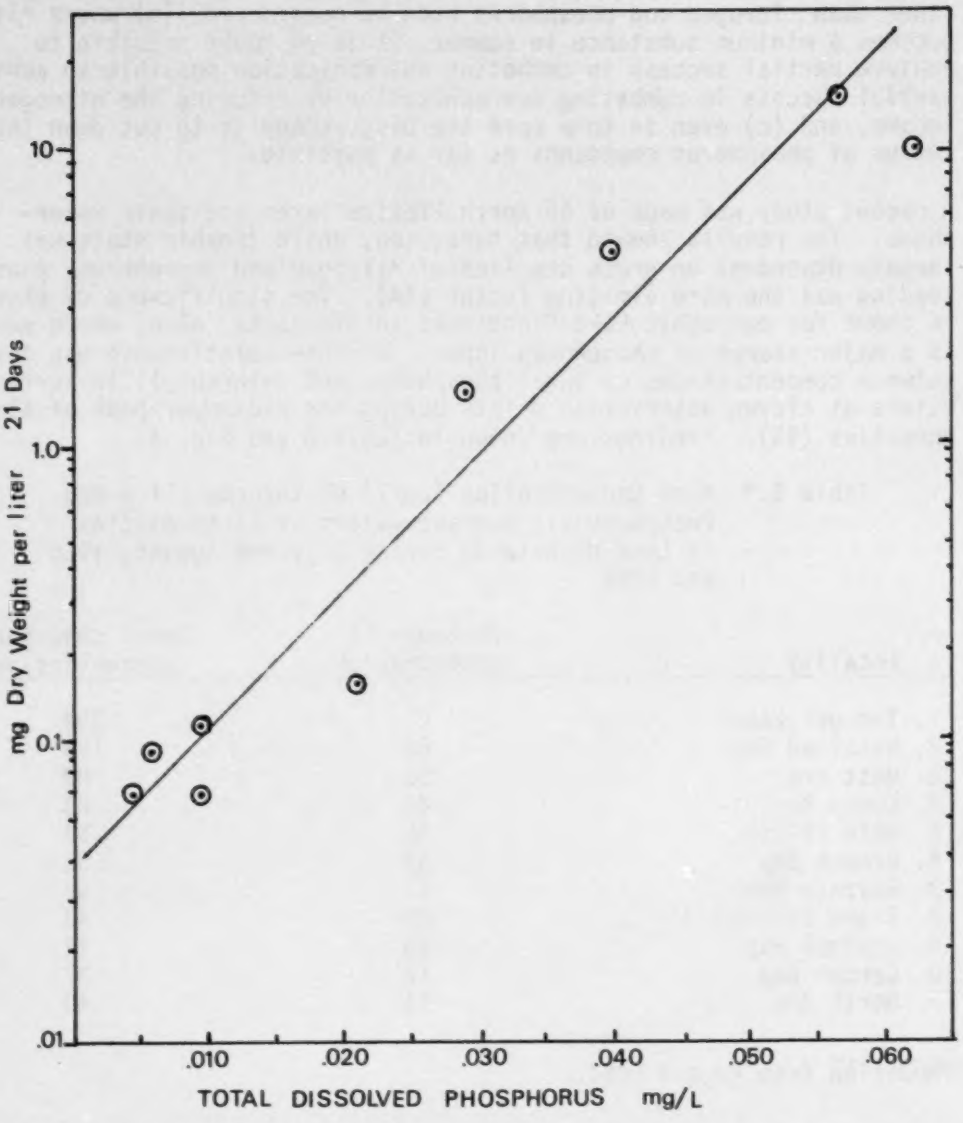

Fig. 3 Algal Yields, as Dry Weight Per Liter, in Oregon Lake Waters Having Phosphorus Content as Shown.

Biological tests, such as algal assays, were used (5, 41, 43) to determine experimentally which of the two factors, nitrogen or phosphorus, is usually limiting in several Swiss lakes. The objective was to facilitate selection of appropriate remedial measures. The results led to the following views: (a) there is no reason to suppose that any substance other than nitrogen and phosphorus need be considered, (b) where nitrogen becomes a minimum substance in summer, it is no doubt possible to achieve partial success in combating eutrophication possible to achieve partial success in combating eutrophication by reducing the nitrogen income, and (c) even in this case the best remedy is to cut down the influx of phosphorus compounds as far as possible.

A recent study was made of 55 North Florida lakes and their watersheds. The results showed that here, too, while trophic state was largely dependent on gross supplies of nitrogen and phosphorus, phosphorus loading was the more limiting factor (44). The significance of phosphorus is shown for eutrophic Lake Minnetonka in Minnesota, also, where sewage is a major source of phosphorus input. A close relationship was found between concentrations of total phosphorus and chlorophyll in surface waters at eleven observation points during the midsummer peak of algal densities (45). Findings are shown in Table 6 and Fig. 4.

Table 6.* Mean Concentration (µg/l) of Chlorophyll a and Phosphorus in Surface Waters at 11 Localities in Lake Minnetonka during July and August, 1968 and 1969.

Locality	Chlorophyll concentration	Total phosphorus concentration
1. Tanager Lake	91	200
2. Halstead Bay	56	119
3. West Arm	50	90
4. Cooks Bay	40	68
5. Gale Island	38	53
6. Browns Bay	33	52
7. Wayzata Bay	31	52
8. Crane Island	25	43
9. Crystal Bay	25	42
10. Carman Bay	12	37
11. North Arm	13	40

*Modified from Megard (45).

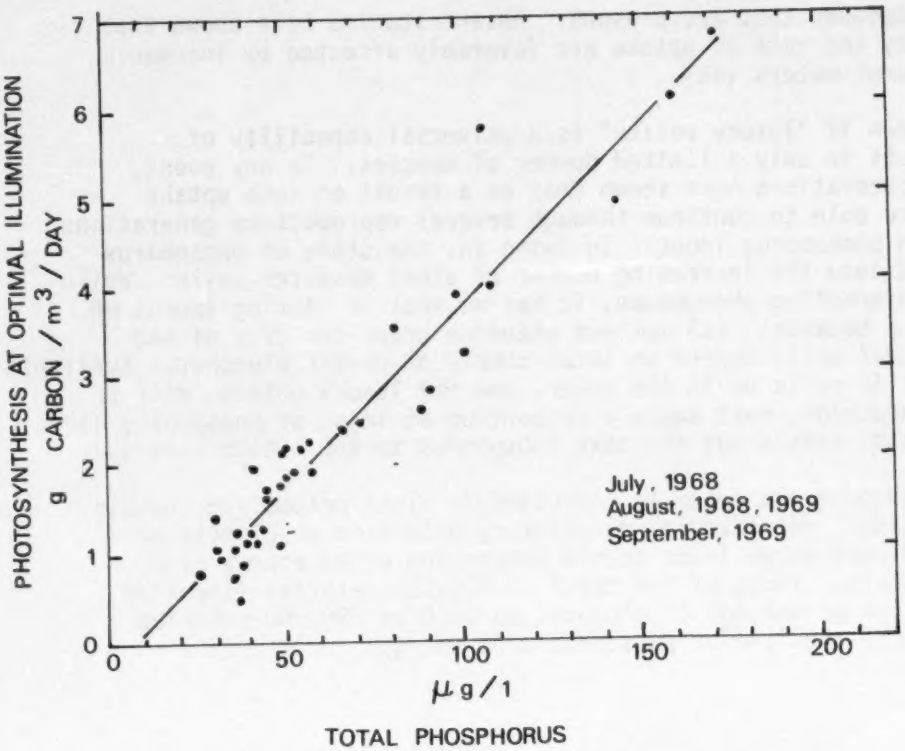

Fig. 4 The Relationship between Photosynthesis at Optimal Illumination and Concentrations of Total Phosphorus in Surface Samples from 11 Localities in Lake Minnetonka. Modified from Megard (45).

It is obvious that phosphorus plays a significant role in the overall process of eutrophication. Phosphorus compounds also play important roles in all phases of algal metabolism--building blocks in the eutrophication process. Many of them are concerned with energy transforming reactions. One of the most important is photosynthesis, in which light energy is used to convert inorganic phosphate to adenosine triphosphate (ATP). ATP is a carrier of energy-rich phosphate and serves as a driving force for many other metabolic reactions.

Because phosphorus in natural environments is mainly as orthophosphate, it is generally felt that algae take up phosphorus from the water in that form. It has been shown, also, that at least some algae have the necessary extracellular enzymes to convert more complex phosphate compounds to orthophosphate to facilitate absorption. Much of the phosphorus incorporated into algal cells occurs as polyphosphates, which apparently accumulate and act as reserves of high-energy phosphate. Thus, the algae are capable of "luxury uptake" of phosphorus and can assimilate in excess of their normal metabolic requirements. Uptake depends not only on phosphorus concentrations in the surrounding water, but also on other factors such as light, hydrogen-ion concentration,

and other compounds that are present. Recent studies have shown that the efficiency and rate of uptake are favorably affected by inorganic salts in natural waters (46).

It is not known if "luxury uptake" is a universal capability of algae or exists in only a limited number of species. In any event, laboratory observations have shown that as a result of such uptake some algae are able to continue through several reproductive generations without added phosphorus input. In doing so, the store of phosphorus is subdivided into the increasing number of algal daughter cells. While this is an interesting phenomenon, it has no real or lasting impact on eutrophication because: (a) maximum standing crop--the crux of bad conditions--must still depend on total supply of usable phosphorus available at the moment in cells or in the water, and (b) luxury uptake, with or without reproduction, must cause a proportion at least of phosphorus-laden defunct cells to settle out and take phosphorus to the bottom (see 45).

Many of the enzymes and coenzymes involved in algal metabolism contain phosphorus, also. For example, respiratory oxidation of glucose to carbon dioxide and water leads to the generation of an energy-rich form of phosphate. Thus, of the total of 680,000 calories liberated in the oxidation of one mol of glucose, as much as 290,000 calories may be stored in the form of phosphate bond energy.

SECTION V

SOURCES OF PHOSPHORUS

Because of the key role of phosphorus in eutrophication, coupled with the present unfavorable prospect of effectively controlling any other nutrient, only phosphorus inputs are emphasized.

All phosphorus inputs are additive and contribute ultimately to phosphorus availability and use by algae in lakes. Therefore, all sources and their inputs must be assessed for amount and seriously considered for control regardless of apparent magnitude. In focusing on major point source inputs, such as municipal sewage and its added detergent phosphorus, too often other potentially significant inputs have been largely ignored. Therefore, summary information on some nine input sources is given, arranged more or less in ascending order of importance.

In considering sources of nutrients, it is logical to think of "natural" ones as opposed to "sources affected by human activities." Among natural sources that help establish long-term baseline eutrophication, we are concerned on a national scale with several: (a) tributary drainage of land areas of great variety ranging from mountain slopes to level plains, from wooded lands to rangeland and prairie; (b) soil erosion, both waterborne and airborne; (c) biological sources, such as excreted droppings from waterfowl, other birds, animals, leaf fall, and nitrogen fixation; and (d) the input from rain, snow, and dust.

Precipitation

While only scanty information is available on significance of the atmosphere and rainfall, there have been observations at widely scattered points in the United States and Europe. It seems apparent that phosphorus inputs, although typically small, are sometimes sufficient to warrant consideration in eutrophication. In general, they range from about 0.015 to 0.06 $g/m^2/yr$ (6, 48). Reported concentrations vary from as little as 0.3 to as much as 130 µg/l. At Corvallis, Oregon, concentrations have been found to range from 2-33 µg/l (29). In Oregon snowfall amounts are similar, but in France as much as 800 µg/l has been found (6). When viewed in context of a troubled lake, precipitation may contribute up to 2 percent of the input, as estimated for Lake Mendota, Wisconsin (15).

Biological Sources

Lakes on flyways used heavily by waterfowl receive nutrients from their droppings. Domestic birds, such as the famous Long Island duckling, excrete about 954 g nitrogen and 408 g phosphorus per bird per year (49). Estimates of nutrient input to lakes by wild ducks have been

based on half this value. Inputs estimated for Upper Klamath Lake from transient waterfowl were considered negligible when related to the total nutrient budget (50). In some waters, however, such as Lake Darling in the Upper Souris drainage in North Dakota, waterfowl may be a major phosphorus source.

There are several other biological phosphorus sources to be noted. Among them are fall-in of leaves, pollen, spores, and insects*. Nitrogen additions may come from fixation by blue-green algae, bacteria, and stream bank red alder (Alnus rubra). Quantitative measurements of such sources appear to have been made only rarely in the context of nutrient budgets of lakes (51).

Gasoline

It is estimated that 2.5 million pounds of phosphorus are consumed annually in the United States in gasoline used by motor vehicles. It is not known how or in what amounts the phosphorus in burned gasoline reaches the Nation's surface waters. In any event, the amount obviously must be less than 2.5 million pounds as based on the following information and assumptions (29):

> Concentrations found in highest of five gasolines purchased in May 1971 in Corvallis, Oregon, area: 12.6 mg P/l (0.1 lb P/1000 gals).
> Assume: 100 million motor vehicles in the United States. Each vehicle consumes 1000 gals/yr. Twenty-five percent of vehicles use phosphorus-containing gasoline.

If the resulting 2.5 million pounds of phosphorus is washed from the air by rainfall evenly over the 3.6 million sq mi of the United States, and if average United States rainfall were 24 in./yr, it is calculated that the concentration of such phosphorus would not exceed 0.0002 mg/l. Actual conditions obviously would give higher localized concentrations.

Boats and Ships

The problem of pollution from watercraft is widespread, because such craft frequent all navigable water areas of the Nation, including many susceptible to eutrophication because they already receive nutrients from a variety of sources. Congregations of pleasurecraft for extended periods can contribute untreated wastes equivalent to the sewage discharge from a small city. Regardless of watercraft size, untreated sewage generally is discharged directly from watercraft today just as it always has been. New treatment devices that comminute and chlorinate onboard wastes will have little or no beneficial effect in decreasing nutrient pollution or preventing eutrophication.

Undisturbed Lands

In looking at tributary drainage from undisturbed lands, it soon becomes apparent that little nutrient information is available; also, that nitrogen and phosphorus contributions per unit area of watershed vary considerably. Such variations are influenced by land slope, soil character, underlying geology, plant cover, amount and nature of precipitation, and many other factors (53). Assessment of natural wooded environments on the west side slopes of the Upper Klamath Lake Basin show annual runoffs of 89 g of nitrogen and 21 g of phosphorus per acre (54). Other sources give woodland contributions of 0.57-1.3 kg nitrogen and 44.5-348 g phosphorus per acre. European figures for Lower Alpine regions are similar at 526 g nitrogen and 105 g phosphorus per acre. Reported runoffs from grassland are similar.

Urban Land

For some time storm water runoff from urban areas has been viewed as a potential pollutant because of the dejecta accumulated in community living--residues from vehicle wear and drippage, garbage from careless handling, pet animal droppings, fertilizing lawns and gardens, and erosion silt (48). Several studies have shown that street runoff is far from clean and contains various pollutional components including considerable phosphorus.

A 1959-1960 study (55) showed that samples of storm water from Seattle street gutters contained up to 0.78 mg/l soluble phosphorus, and up to 1.4 mg/l total phosphorus. The highest concentrations usually were found when antecedent rainfall had been low. Storm water runoff in the Cincinnati area contained an average concentration of 0.36 mg/l PO_4-P (48). In another study (56) the maximum total phosphorus concentration observed in separate storm water at Ann Arbor, Michigan, was 5.3 mg/l. The maximum concentration from a combined system at Detroit was 14.1 mg/l. Dilution of 36 to 1400 times would be required for these runoffs to attain a tolerable target level of 0.01 mg/l.

In 1960, the Nation's urban land had a total area of about 25,544 sq mi and contained a population of about 85,800,000--somewhat more than half of the United States population (57). For that time the phosphorus contribution from such land to storm or combined sewers with a 30-inch annual rainfall would vary from 11-170 million pounds per year based on an estimated total phosphorus concentration of 0.1-1.5 mg/l.

Industry

We know little about industries as nutrient sources except that there are some, depending on process and raw materials, that can shed phosphorus in their wastes. But there is no real knowledge, even today on a national scale, as to how many factories are involved or how much

these input quantities may be. It is known, however, that important users of phosphorus were as shown below (Table 7). Some information in this regard is available for German industries also and is given (Table 8).

U. S. data (62) show that combined phosphorus loads generated by fruit and vegetable processing amounts to roughly 10 million pounds per year. Some 50-60 percent is discharged to municipal sewers and the remainder goes to industrial waste treatment plants or directly to receiving streams.

Table 7. Commercial Phosphorus Consumption in the United States (million pounds)

	1958 (58)	1965 (59)	1968
Fertilizers	1980	3098 (60)	7320 (60)
Built detergents	376	--	506*
Animal feeds	238	207	--
Water softening	57	--	--
Pharmaceuticals, foods	37	--	--
Surface treatment of metals	31	--	--
Plasticizers, gasoline additives and insecticides	20	23	--
Other	91	843	--
Total	2830		

*Based on 4 percent increase from the 486.8 million pounds reported for 1967 (61).

Table 8.* Phosphorus Concentrations in German Industrial Wastes

Type of waste	Phosphorus mg/l
Beet sugar factories:	
Wash water	2.6 - 13
Press water	31 - 274
Potato starch	27 - 80.5
Dairy	0.9 - 1.3
Malt-house	13
Brewery	20.2
Slaughter-house	8.2
Rendering plant	43.7
Flax retting	26.1
Starch	76.5
Dairy	8.7

*Modified from Vollenweider (6).

Agricultural Lands

It has been pointed out that eutrophication due to man's activities is as old as history. In 1825 the blue-green alga, Oscillatoria rubescens, believed by some to be an early sign of eutrophication, first appeared in Lake Murten in Switzerland (63). This was believed to have been stimulated by nutrient runoff from newly tilled lands.

In looking at the impact of agriculture, it is not necessary to review the many complex interrelationships examined recently in great detail by Vollenweider (6). Related to them are: soil types, leaching charactertistics, slopes, fertilization practices, animal populations, manure compositions, feedlot practices, and silo drainage. It is enough to say that, in general, agricultural lands yield more nitrogen and phosphorus in runoff than undisturbed and natural lands. The Williamson and Sprague Rivers in the Upper Klamath Lake Basin drain lands that are devoted 90 percent to production of forage and feed grains and 10 percent to grazing (50). Runoff losses of nitrogen and phosphorus are twice as great as for nearby nonagricultural lands. In other areas of the United States, orchards have been found to yield four times as much phosphorus and 30 times as much nitrogen as grass and woodland (54). Losses from grain-crop areas were found to be even greater.

In some irrigated areas in the watershed of Upper Klamath Lake, annual nitrogen losses to irrigation drain-water are as great as 0.1 to 11 kg/acre and phosphorus losses range from 0.2 to 4.0 kg/acre (29). The significance of agricultural drainage depends on how much nutrient finally reaches the responsive waters, regardless of the hydrologic pathway.

In some farming areas, nutrient losses from barnyards, manure spreading (53), and feedlots are special points of concern. It has been estimated that animals currently under confined feeding in the United States yield pollutional wastes equal to sewage from 850 million people (64). When considering, in addition, the frequent and unfortunate practice of feeding livestock on hillsides adjacent to streams, the avenues for nutrient input are quite wide open.

In addition to runoff of dissolved nutrients, unmeasured quantities are carried along with erosion sediments. As the Mississippi River drains the "Great Breadbasket" of the United States, it alone carries nearly 450 million metric tons of sediment to the Gulf annually (65). But elsewhere other drainages enter lakes and reservoirs, filling up the bottom and yielding nutrients into solution. Human activities such as construction of highways, urban complexes, forest roads, logging, overgrazing, and poor farming practices, greatly increase the erosion input.

Municipal Sewage

Accelerated eutrophication in many lakes in the United States, Europe, and elsewhere has been stimulated by and appeared concurrently with increasing inputs of municipal sewage. That sewage plays a major role in this resource destruction has been known for many years. Noted examples of such impact are the lakes at Madison, Wisconsin, Zürichsee in Switzerland, Lake Washington at Seattle, Lake Erie, and the Potomac Estuary (66). These bodies of water exemplify the situation in which sewage was, and in some cases still is, the major point source of phosphorus. It is important, therefore, to examine this source in some detail.

Sewage derives nutrients, including phosphorus, from several sources. As expected, the amounts of phosphorus remaining after partial removals through treatment in the sewerage system are carried along with the sewage when discharged to the environment. It is estimated (29) that in 1968 the United States sewered population of 137 million people discharged 376 million pounds of phosphorus to receiving waters (Table 9). This is potentially controllable phosphorus and corresponds to 2.74 lbs P/capita/yr. Of the some 3.5 pounds of phosphorus per person per year discharged in raw wastewater (i.e., before treatment), 1.2 pounds come from human excretion and 2.3 from other sources (67). Therefore, with an average 22 percent reduction through sewage treatment as shown in Table 10, a total of 129 million pounds originating in human excretion reaches the water system annually (0.94 lb P/capita) and a total of 247 million pounds in sewage from other sources (1.8 lbs P/capita).

Table 9. Estimated Quantity of Phosphorus Discharged to Receiving Waters in the U. S. in 1968 from the Sewered Population

Source of phosphorus	Amount of phosphorus as P (million pounds)
Human excretion	
Soft drinks	2.5
Beer	2.5
Other	124.
Detergents	222.*
Other sources	25.
Total	376.

*Based on 104 percent of the 213 million pounds reported for 1967 (61).

Table 10.* Estimated Phosphorus Removals by Municipal Sewage Treatment in 1968

Type of treatment and population served (68)	Efficiency of removal (67)	Pounds of P discharged (3.5 lbs P/capita/yr) (67)
1. No treatment 60×10^6	--	210×10^6 (uncontrolled)
2. Raw sewage 6×10^6	0	21×10^6
3. Primary-intermediate 43×10^6	10%	135×10^6
4. Activated sludge 41×10^6	40%	86×10^6
5. Trickling filter 28×10^6	25%	74×10^6
6. Miscellaneous	10%	60×10^6

*From Barth (67).

One of the metabolic sources of phosphorus in sewage is soft drink consumption; another is beer. A recent report (69) shows that almost 300 units of soft drinks are consumed annually per capita in the United States. Of this amount, 65 percent are cola drinks. Analyses of various soft drinks obtained in the Corvallis, Oregon, area in May 1971 showed the following phosphorus content (29):

Seven brands of cola drinks ---- 112-240, av. 161 mg/l ortho-P

Five brands of non-cola drinks - 0.11-3.54, av. 2.4 mg/l ortho-P

Because cola drinks contain an average of 161 mg P/l, represent 65 percent of the soft drinks consumed in the United States, and because other soft drinks with one exception contain relatively small amounts, the phosphorus contribution to the environment is estimated only for cola drinks. On this basis 3.2 million pounds of phosphorus were contained in the cola drinks consumed by the 137 million sewered population assuming a 12 oz per soft drink unit. If one allows 22 percent removal by various waste treatments, this yields 2.5 million pounds of phosphorus reaching the water systems in the United States in 1968.

Similar contribution of phosphorus through consumption of beer is estimated to have been 2.5 million pounds in 1968 (29). This is based on the following 1968 information (70):

U. S. population over age 18	129 million
Per capita annual U. S. consumption of beer by over 18 group	25.88 gallons

Analyses of four samples of beer including a bottle and can of each of two nationally marketed brands purchased in the Corvallis, Oregon, area in May 1971 showed the following phosphorus content (29):

	Ortho P - mg/l
Brand A (bottle)	155
Brand B (can)	190
Brand B (bottle)	146
Brand B (can)	137
Average	157

With the above information and assuming 69.6 percent of the over 18 population connected to sewers and 22 percent of the sewered phosphorus removed by treatment, then 2.5 million pounds of the phosphorus in beer reached United States water systems in 1968.

Other estimates (57) based on nutrient removals by waste treatment suggest annual sewage discharges to surface waters of 200-550 million pounds of phosphorus and 1.1-1.6 billion pounds of nitrogen. Assuming these estimates are reasonable (our own estimate [29] of 376 million pounds of phosphorus is within this range), it appears the expected nitrogen/phosphorus ratios are in the range of 3 to 6. This is in general agreement with specific observations (71) that under optimal operating conditions, the effluent from an activated sludge plant had 17.1 mg/l total nitrogen and 7.3 mg/l total phosphorus, giving a nitrogen/phosphorus ratio of 2 to 3.

The phosphorus content of domestic sewage is about 3 to 4 times the level found before the advent of synthetic detergents (72) at about 1945. Sawyer (73) estimated the 1950 detergent industry contribution at about 1.6 lb P/capita/yr. A 1955 estimate (74) is 1.9 lbs P/capita/yr. A Task Force estimate for 1958 (57) gives 2.1 pounds. These estimates of increasing amounts apparently relate to increased popularity of detergent use. This is evident from the progressively increasing production from 1945 to recent times (Table 11). Phosphorus consumption in detergent formulations is second only to consumption in fertilizer (57).

The laundry soaps of yesteryear were manufactured from fatty acids and saponified rosin and then fortified with silicates of soda, soda ash, at times with borax, and/or up to five percent trisodium phosphate as a replacement for soda ash and borax (78). Today's marketed detergent contains the constituents shown in Table 12 (79). The major ingredient noted is sodium tripolyphosphate. Data on the levels of sodium

tripolyphosphate as found in analyses conducted by and for the Federal Water Quality Administration are presented in Table 13 (80). For household detergents amounts range from 18.6 to less than 0.25 percent.

Table 11.* Detergent History

Year	Production of synthetic detergents millions of pounds	Production of P for detergents millions of pounds
1945	83	
1950	1030	130 (est.)
1955	2330	
1960	3330	380
1965	4160	500
1968	4730	630 (est.)

*From (76,77)

While a national average appears unavailable, a recent source (75) estimates that approximately 50 percent of the municipal phosphate discharges in Canada to lakes Erie and Ontario is from detergents. In the United States the corresponding figure is 70 percent. Based on these values, it is estimated that detergent phosphorus accounts for 40 percent of the total input to the two lakes. If these figures are essentially correct, detergents obviously then are a substantial source of phosphorus and can be a significant contributor to eutrophication. Where phosphorus is present in large amounts, algal and plant growth will increase until another nutrient will eventually become growth-limiting. Since nitrogen is usually the second most important growth-limiting nutrient, agricultural run-off, which is often particularly high in nitrate-nitrogen, would further enhance the eutrophying effects of detergent phosphorus.

Table 12.* Synthetic Detergent Formulas

	Heavy duty product US - Canada	Light duty powders All countries	Light duty liquids All countries	Detergent laundry bars
Active ingredient (e.g., alkylbenzene sulfonate, fatty alcohol sulfate)	14-20%	25-32%	30-37%	20-25%
Foam Booster (e.g., lauryl alcohol cocomonoethanolamide)	1.5-2%		5-12%	
Sodium tripolyphosphate	40-60%	2-15%		15-25%
Anti-soil redeposition agent (e.g., sodium carboxy methyl cellulose)	0.5-0.9%			0.3-0.5%
Anti-corrosion agent (e.g., sodium silicate)	5-7%	0.02-0.08%		3-8%
Optical brightener	0.30-0.75%			0.05-0.25%
Enzymes	0.20-0.75%			
Moisture	6-12%	1-4%		3-8%
Ethanol or sodium xylene sulfonate			6-9%	
Sodium bicarbonate				15-20%
Sodium carbonate				15-30%
Filler (e.g., sodium sulfate)	0.32%	60-68%		

*From Silvis (79).

Table 13.* Concentration of Phosphorus in Detergent Formulation as Percent Phosphorus**

(1% = 10,000 mg/kg)

	% P
Pre Soak	
Biz	18.6
Enzyme Brion	18.0
Amway Trizyme	18.0
Axion	15.9
Laundry Detergents	
Blue Rain Drops	15.9
Salvo	14.3
Tide	12.6
Amway SA-8	12.4
Cold Water Surf	12.2
Drive	12.0
Oxydol	11.8
Bold	11.5
Cold Water All (powder)	11.5
Ajax Laundry	11.3
Cold Power	11.3
Punch	11.2
Dreft	10.6
Rinso with Chlorine Bleach	10.3
Gain	10.0
Duz	9.7
Bestline B-7	9.6
Bonus	9.5
Breeze	9.4
Cheer	9.2
Fab	8.8
White King with Borax	8.8
Royalite	5.5
Instant Fel Soap	4.2
Wisk (liquid)	3.6
Laundry Detergents (cont.)	
Par Plus	1.1
Addit Liquid	0.6
Ivory Liquid	0.5
Lux Liquid	0.5
White King Soap	.25
Cold Water All (liquid)	.25
Automatic Dishwasher Detergents	
Amway	15.1
Cascade	13.8
All	13.6
Calgonite	12.5
Electrosol	8.8
Household Cleaners	
Ajax All Purpose	7.2
Mr. Clean	6.8
Whistle	0.8
Pinesol	.25
Miscellaneous	
Snowy Bleach	9.2
Borateem	.25
Downy	.25

* From Eiserer (80).

** The P values of this table were calculated from the $Na_5P_3O_{10}$ values in the reference.

SECTION VI

CONTROL OF EUTROPHICATION

Intense reflection on possible approaches to restore lakes or control eutrophication yields only five major possibilities. The first includes efforts to limit fertility in water, a necessary first step in every problem lake; and second, to improve the food web so that a harvestable and valuable crop such as fish, could be produced with a concomitant removal of nutrients; third, to stimulate diseases and parasites among the unwanted plants to keep them under control; fourth, to recycle nutrient laden waters to agricultural and forested areas for fertilization and to prevent re-entry of the nutrients to surface waters; and fifth, to use toxic chemicals to kill aquatic vegetation. These options are in decreasing order of choice. Some are now only ideas.

For many years eutrophication control efforts have emphasized obliterating the most onerous symptoms of the process--excessive algae, waterweeds, and fill-in. Since 1903 (82) copper sulfate and more recently developed algicides have been used to treat lakes for temporary relief from algal blooms. Sodium arsenite served a similar purpose to control unwanted waterweeds but has been largely replaced by other aquatic herbicides. Fill-in from accumulated silt input, settling algal remains, and centripetal growth of encroaching floating bog has been attacked by dredging in efforts at lake rejuvenation. Because these and several other mechanical approaches do not really seek to correct the root causes of the problem, the results usually are short-lived and futile as a true solution.

Without question, the soundest preventive and restorative approach that seeks to correct the root cause is to curb nutrient input. Every nutrient source is important and eventually must be examined for control possibilities, but first attention must be directed to sources for which there is now control capability. The major nutrient control procedure available and practical in the United States at this time is treatment of sewage or other wastes to strip them of their nutrient content. Naturally, the question arises as to what nutrient or nutrients should be removed. The answer can be derived in rational fashion.

In studying Table 1, obviously, one could consider carbon, nitrogen, phosphorus, micronutrients, or any other elements as potential targets for control. In keeping with Liebig's Law, theoretically it would be possible to limit production if any one or more nutrients could be reduced to critical levels. As already pointed out, such conditions commonly prevail naturally in oligotrophic lakes where there may be limitations of phosphorus, sometimes nitrogen, and less commonly carbon and lesser nutrients--iron (83), molybdenum (84), silica (85) and others (86).

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Based on this fundamental knowledge, coupled with conclusions from the long period of scientific study and experience with lakes and the findings from laboratory and specific lake studies in the countries most concerned with eutrophication, two principal remedial approaches have emerged. In the first, sewage is collected and directed away from lakes to less susceptible waters as in: (a) Madison, Wisconsin, lakes (81); (b) Lake Washington, in Seattle (37); (c) Zürichsee and Hallwillerzee, in Switzerland (5); (d) Tegernzee and Schlierzee, in Germany (39); Zellersee, in Austria (5); and (e) Annecy and Nantua Lakes, in France (87). This approach has proved effective but, unfortunately, cannot be used in many locations that lack favorable watercourses to receive diverted sewage flows.

In the second, the objective is to curtail input of one selected nutrient, namely phosphorus, through advanced waste treatment processes and through limiting phosphorus contributions to sewage via synthetic detergents. The logic of curtailing phosphorus input through advanced treatment has been widely accepted--even by many persons who take an opposite view on the necessity to eliminate phosphorus from detergents. Many actions to control eutrophication, already underway, are based on this waste treatment approach. Examples are: (a) abatement programs for all of the Great Lakes except Lake Huron; (b) Upper St. Lawrence River; (c) Potomac River and estuary; (d) state legislation passed or under consideration to set municipal waste effluent standards for phosphorus; and (e) city, state, and federal legislation passed or under consideration to regulate phosphorus content of detergents primarily so as to decrease quantities in sewage that must be removed by treatment.

In spite of the logic, need and scientific base for those actions, intense efforts have sought to focus attention on other nutrients and lead the emphasis away from phosphorus. During the last two years, or a little longer, a campaign has been waged by a small group to establish a position that "We (U.S. and Canada through the International Joint Commission) Hung Phosphates (by advocating elimination of phosphorus from detergents) Without a Fair Trial" (88). The crux of this accusation seems to be nurtured by three papers that emphasize the role of carbon in algal nutrition and in lakes (89, 90, 91). The position is taken that carbon and not nitrogen or phosphorus is the "key" nutrient in eutrophication. This, in turn, forms the basis to advocate that control efforts be focused on carbon and not on phosphorus.

This issue, in part referred to as the "Lange-Kuentzel-Kerr" thesis, has been debated thoroughly and repeatedly within the scientific community and has been found scientifically inadequate as a basis for eutrophication control (92). The most recent debate was a Symposium on Nutrients and Eutrophication, "The Limiting Nutrient Controversy," sponsored by the American Society of Limnology and Oceanography, held at Gull Lake, Michigan, on February 10-12, 1971. The proceedings are in press, but a summary statement prepared at close of the meeting (93) says, "...one generalization seemed to emerge--that the efforts to remove phosphorus from influents to

lake ecosystems is not a waste of time and money.... It was generally agreed by the participants that the only realistic option for controlling or reversing cultural eutrophication in lakes is to remove phosphorus from the influent waters."

Because some of the stimulated confusion still persists, several pertinent points are offered:

1. The "Lange-Kuentzel-Kerr" thesis is not accepted by numerous scientists throughout the world who have given their professional attention to this problem for many years.

2. The considered conclusion of such scientists holds that nitrogen and phosphorus universally are the most significant nutrients in eutrophication, with phosphorus typically the limiting nutrient in oligotrophic lakes.

3. Recent algal assays have shown the importance of phosphorus in relation to carbon and nitrogen (29). When carbon, nitrogen, and phosphorus were added singly and in combination to water from lakes of nine different levels of fertility, maximum standing crops of an introduced test alga were directly proportional only to phosphorus, and had no obvious correlation with carbon or nitrogen.

4. At Lake Washington, in 1957, sewage effluents contributed 56 percent of total phosphorus and 12 percent of nitrogen inputs. Following progressive diversions begun in 1963 to control eutrophication (see Fig. 2), phosphate decreased 72 percent by 1969 and algae (as shown by chlorophyll) followed the same pattern, decreasing about 80 percent. Concurrently, nitrate decreased by only 20 percent or less, and free CO_2 fluctuated around 75 percent of the original level, neither showing a positive relationship to algal production. This performance is considered a valid basis to predict improvement in similar lakes through phosphorus limitation (37).

5. A recent paper discussing nutrient control policies in Canada points out that the total pollutant BOD input to Lake Erie has a carbon equivalent of 75,000 tons (75). In contrast, the lake's bicarbonates (with 20-25 ppm C) equal 10-12.5 million tons of available carbon, or about 150 times the amount from an entire year's input of sewage. At peak of the growing season, the biomass of 4.9 million tons contains 1.8 million tons of carbon, a value far exceeding the amount potentially controllable in pollutant inputs. Obviously, also, the carbon available in bicarbonates--not to even mention the additional free CO_2 from the atmosphere and from microbiological decomposition of organics--far exceeds the demands of algal production. The ratio of carbon in bicarbonates to the lake's total phosphorus is 800:1. If the carbon/phosphorus ratio

in algae is about 40 (see page 14), then there is 20 times more bicarbonate carbon available than required to completely deplete the water of phosphorus. Similarly, Lake Erie has a six-fold surplus of nitrogen, assuming a nitrogen/phosphorus ratio of 7. These calculations show that in Lake Erie, as in many other lakes, it is phosphorus and not carbon that is the growth limiting element.

6. Experimental efforts by Morton (94) to limit algal growth by carbon dioxide control were not successful in waters open to the atmosphere. He found that the atmosphere supplied adequate CO_2 to water depths of 5.5 feet to support algal production of 2 mg/l/d, even without turbulent mixing.

7. Vallentyne (40) presented many of the arguments against the "Lange-Kuentzel-Kerr" thesis. The reader is referred to his entire paper, but following is one of the most significant aspects that can be derived from his statement.

As shown in Table 14, of all nutrient elements known to be growth-controlling in lakes, only phosphorus is also controllable by man. Carbon is too ubiquitous and is not controllable and nitrogen only partly so. There are several reasons why nitrogen is only partly controllable. In its various forms, as nitrate, ammonia, and organic, it enters lakes from natural and cultural sources much more readily than phosphorus. Avenues of entry are surface and subsurface soil drainage, rain, snow, dust, and fixation of atmospheric nitrogen by some blue-green algae and other microorganisms. While sewage sources may contribute high percentages to total phosphorus inputs, sewage provides lower percentages of total nitrogen inputs--56 percent vs. 12 percent for Lake Washington. These differences reflect the difficulty in effectively controlling nitrogen.

Table 14.* Comparison of Various Plant Nutrients in Respect to (A) Whether They are Ever Growth-Controlling in Lakes and (B) Whether They are Controllable by Man. Elements Listed in Order of Increasing Atomic Weight. Note that Phosphorus is the Only Element Meeting Both Requirements.

Nutrient	A	B	Nutrient	A	B
Hydrogen	no	no	Chlorine	no	no
Boron	no	no	Potassium	no	no
Carbon	rarely	no	Calcium	no	no
Nitrogen	yes	partly	Manganese	sometimes	no
Oxygen	no	no	Iron	sometimes	no
Sodium	no	no	Cobalt	rarely	no
Magnesium	no	no	Copper	no	no
Aluminum	no	no	Zinc	no	no
Silicon	yes**	no	Molybdenum	sometimes	no
Phosphorus	yes	yes	Iodine	no	no
Sulphur	rarely	no			

* From Vallentyne (40)
**Diatoms only

On the other hand, it is safe to assume that human activities that contribute phosphorus are the only significant cause of declining nitrogen/phosphorus ratios. Therefore, this growing imbalance can be corrected only by appropriate adjustment in human affairs. It is recognized that all phosphorus inputs cannot be eliminated. Those that can be controlled should be brought under control as soon as possible. Once the major inputs are effectively controlled, the naturally occurring concentrations of calcium, aluminum, iron, and biological systems will serve as phosphorus sinks, and hydrologic flow-through will help decrease fertility.

SECTION VII

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